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CIGS Thin-Film Solar Cell Research at NREL: FY04 Results and Accomplishments

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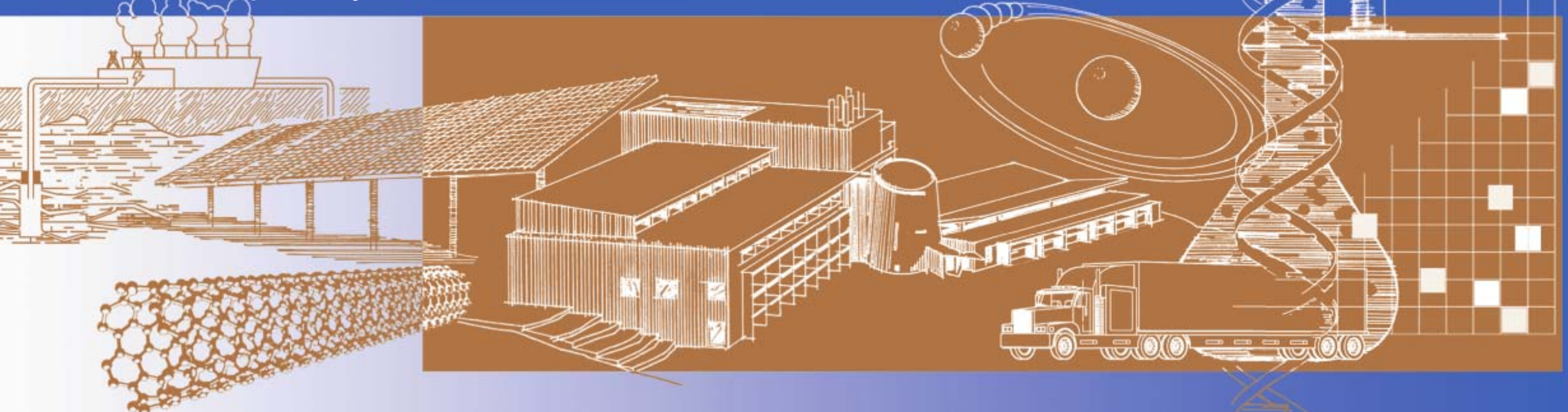

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ABSTRACT

This short paper is a summary of our investigations in three major areas: high-efficiency $CuInGaSe_2$ (CIGS) solar cells, junctions made using chemical bath deposited ZnS(O,OH) buffer layers, and solar cells fabricated from thinner absorbers. Significant progress was made in all areas. We describe how our research has contributed to the fundamental understanding and the practical application of CIGS materials to high performance solar cells.

1. Objectives

Polycrystalline thin film solar cells made from $CuInSe_2$ (CIS) alloys have begun to fulfill the promise of low-cost, power generation from non-polluting, clean energy sources. The efficiency of laboratory scale solar cells is now well over 19%, and that of commercial modules is around 13%. These are astounding milestones when we take into account the inadequate knowledge-base (unlike Si). Ironically, it is the lack of fundamental understanding of interface and junction properties that is now the dominant theme in our discussions. The issues identified by the CIS National Team illustrate this point. The task at hand is still the need to correlate the properties of the absorbers and junction formation processes to the properties of the solar cells. The diversity in the deposition processes employed at the various laboratories adds another dimension to the challenge. It is our hope that lessons learned from a careful study of the laboratory scale systems can be translated to "real-life" devices made by our industrial partners. The work reported here will provide some examples to illustrate this point. This paper is not a comprehensive report of all the work performed in Cu-ternary compounds at NREL. The reader is referred to other papers in these proceedings.

2. Technical Approach

The three-stage process continues to serve as a benchmark for polycrystalline CIGS solar cells and a model system to be compared with materials and devices made by other processes. Experimental procedures for fabricating CIGS absorbers and the deposition of CdS and ZnO window layers have been described in detail elsewhere [1]. In this study, a variation of the overall Ga fraction was obtained by varying the Ga content during the first stage of deposition. The effective bandgap of the absorber was thus varied from 1.1-1.2 eV. ZnS(O,OH) buffer layers were grown by a novel CBD process developed at NREL. In an attempt to address concerns about the scarcity of In, we have begun work on thinning the CIGS absorber layers. The three-stage process was modified to fabricate absorber layers with a thickness around 1 µm.

3. Results and Accomplishments

First, we describe the properties of solar cells fabricated from absorbers with varying Ga content. Good columnar growth was observed in the range of samples prepared. Compositional profiles show that the Ga is graded from back to front as a result of the out-diffusion of Ga during film fabrication. Table I shows a summary of solar cell properties measured under standard reporting conditions (XT-25). Cell efficiencies above 19% are observed for a range of bandgaps. Fill factors in excess of 80% are obtained *in conjunction* with the higher voltages. This data suggests that it is possible to move the optimum bandgap to about 1.2 eV and still achieve high performance solar cells with high voltages. An analysis of the current-voltage curves shows that the junctions are characterized by low ideality factors and low reverse saturation current densities. Further improvements are possible by improving the short wavelength collection and minimizing the optical losses.

Table I. Parameters of high-efficiency CIGS solar cells.

Sample Number	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Efficiency (%)
S2212B1-3	0.701	34.60	79.65	19.3
S2212B1-4	0.704	34.33	79.48	19.2
S2212B1-5	0.703	34.08	79.23	19.0
S2213A1-3	0.740	31.72	78.47	18.4
S2213A1-4	0.737	31.66	78.08	18.2
S2229A1-3	0.720	32.86	80.27	19.0
S2229A1-5	0.724	32.68	80.37	19.0
S2229B1-2	0.731	31.84	80.33	18.7
S2229B1-4	0.728	31.87	80.16	18.7
S2232A1-3	0.703	33.94	79.67	19.0
S2232A1-4	0.704	33.83	80.09	19.1
S2232B1-2	0.717	33.58	79.41	19.1
S2232B1-3	0.713	33.38	79.54	18.9
C1812-11	0.692	35.22	79.87	19.5 New record

The next section of this paper is concerned with our continued efforts towards understanding the basic mechanisms involved in the formation of photovoltaic junctions in CIGS solar cells. Our work in this area has been done in conjunction with the CIS National Team and several industrial partners. For example, cadmium partial electrolyte (Cd PE) treatment was developed on NREL absorbers and extended to Shell Solar (SSI) absorbers. During the current period, we were involved in a joint experimental study with the Absorber and Junction subteams of the National Team. The absorber team attempted to find a "figure of merit" that will enable us to distinguish a "good absorber" from a "bad absorber." NREL absorbers and devices were provided for this study to serve as a "benchmark" for comparisons with other devices. Correlations between deep-level density and device performance was established. An unexpected, and possibly more interesting and useful outcome of this exercise was the remarkable difference in the performance of solar cells fabricated from SSI absorbers where the window layers were processed at SSI and NREL. This illustrates the power of electronic interactions that occur during the fabrication.

In the area of non-CdS buffer layers, we have fabricated solar cells using CBD ZnS(O,OH) layers on NREL absorbers and SSI absorbers simultaneously. In fact, the latter were used for the bulk of the process development work, and a 14.4%-efficient solar cell was fabricated. The deposition method is new and offers some advantages over other approaches. High-efficiency CIGS cells have been fabricated without the need to do multiple coatings or extensive post-anneals. At the time of writing this report, 18.5% efficient cells have been fabricated on NREL absorbers [2,3]. The quality of the junctions appears to be quite good as evidenced by the absence of light soaking effects. The process is reproducible, and we have fabricated high efficiency cells on absorbers produced over a year.

The third area of investigation reported here concerns the reduction of absorber layer thickness. The price of Indium, its availability, and the extraordinary rate of consumption by the flat panel display industry trigger concerns in the CIS community. One solution to this problem is to limit the amount of In used without sacrificing the performance of the cells. We have fabricated a few absorbers with a nominal thickness of 1-µm by making some modifications to the standard three-stage runs. The microstructure of the absorbers is similar to our standard absorbers, and the elemental compositions obtained by electron probe microanalysis are also similar. Figure 1 shows the scanning electron microscopy (SEM) cross sectional image of a 1-µm thick absorber.

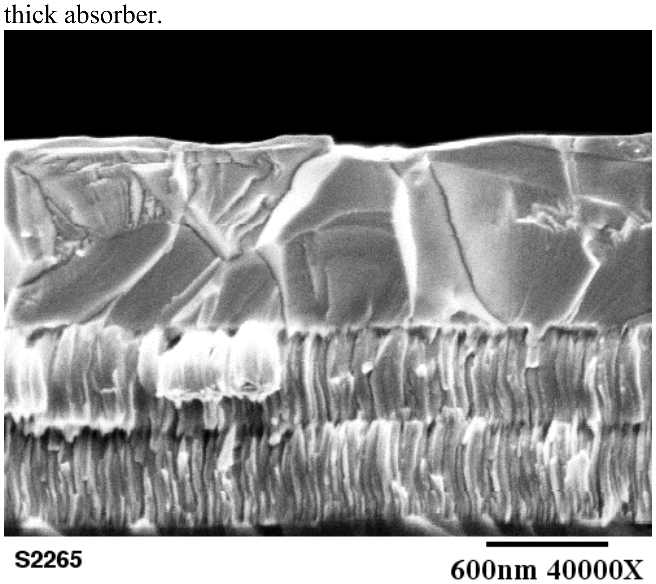

Fig. 1. SEM image of a thin CIGS absorber.

Solar cells fabricated from this absorber exhibited open circuit voltages in the range of 650-660 mV, current density of 32-33 mA.cm^{-2}, fill factors of 77-78%, and the best conversion efficiency was 16.5%. The external quantum efficiency of a solar cell is shown in Fig. 2.

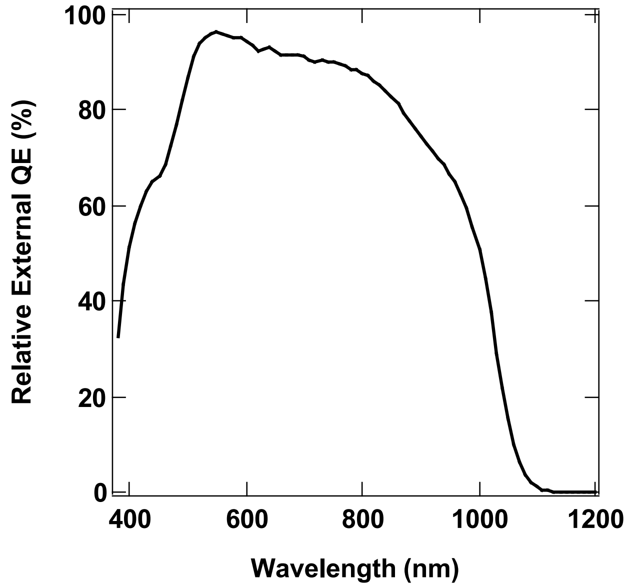

Fig. 2. External QE of a thin CIGS solar cell.

The spectral response curve shows a decrease of the long wavelength collection. This is most likely due to incomplete absorption of the carriers generated by the red photons and requires further study. We shall pursue this work in support of the Thin Film Partnership Program.

4. Conclusions

We have shown significant progress in the reproducible fabrication of high efficiency CIGS solar cells with a range of bandgaps (1.1-1.2 eV). The highest conversion efficiency is now 19.5%. High-efficiency cells have also been fabricated using CBD ZnS(O,OH) layers. The superior short wavelength collection is an obvious attraction. We have fabricated a 16.5% efficient cell using 1-µm thick CIGS absorbers grown by the three-stage process. We have also made significant contributions to the work of the CIS National Team during this period.

Acknowledgments

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[1] K. Ramanathan, et al., presented at the E-MRS meeting, Strasbourg, France, May 2004, to appear in *Thin Solid Films*.

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